by Lawrence M. Krauss and Glenn D. Starkman

Eternal Life

Eternal life is a core belief of many of the world's religions. Usually it is extolled as a spiritual Valhalla, an existence without pain, death, worry or evil, a world removed from our physical reality. But there is another sort of eternal life that we hope for, one in the temporal realm. In the conclusion to Origin of Species, Charles Darwin wrote: "As all the living forms of life are lineal descendants of those which lived before the Cambrian epoch, we may feel certain that the ordinary succession by generation has never once been broken .... Hence we may look with some confidence to a secure future of great length." The sun will eventually exhaust its hydrogen fuel, and life as we know it on our home planet will eventually end, but the human race is resilient. Our progeny will seek new homes, spreading into every corner of the universe just as organisms have colonized every possible niche of the earth. Death and evil will take their toll, pain and worry may never go away, but somewhere we expect that some of our children will carry on.

Or maybe not. Remarkably, even though scientists fully understand neither the physical basis of life nor the unfolding of the universe, they can make educated guesses about the destiny of living things. Cosmological observations now suggest the universe will continue to expand forever— rather than, as scientists once thought, expand to a maximum size and then shrink. Therefore, we are not doomed to perish in a fiery "big crunch" in which any vestige of our current or future civilization would be erased. At first glance, eternal expansion is cause for optimism. What could stop a sufficiently intelligent civilization from exploiting the endless resources to survive indefinitely?

Yet life thrives on energy and information, and very general scientific arguments hint that only a finite amount of energy and a finite amount of information can be amassed in even an infinite period. For life to persist, it would have to make do with dwindling resources and limited knowledge. We have concluded that no meaningful form of consciousness could exist forever under these conditions.

The Deserts of Vast Eternity

Over the past century, scientific eschatology has swung between optimism and pessimism. Not long after Darwin's confident prediction, Victorian-era scientists began to fret about the "heat death," in which the whole cosmos would come to a common temperature and thereafter be incapable of change. The discovery of the expansion of the universe in the 1920s allayed this concern, because expansion prevents the universe from reaching such an equilibrium. But few cosmologists thought through the other implications for life in an ever expanding universe, until a classic paper in 1979 by physicist Freeman Dyson of the Institute for Advanced Study in Princeton, N.J., itself motivated by earlier work by Jamal Islam, now at the University of Chittagong in Bangladesh. Since Dyson's paper, physicists and astronomers have periodically reexamined the topic [see "The Future of the Universe," by Duane A. Dicus, John R. Letaw, Doris C. Teplitz and Vigdor L. Teplitz; Scientific American, March 1983]. A year ago, spurred on by new observations that suggest a drastically different long term future for the universe than that previously envisaged, we decided to take another look.

Over the past 12 billion years or so, the universe has passed through many stages. At the earliest times for which scientists now have empirical information, it was incredibly hot and dense. Gradually, it expanded and cooled. For hundreds of thousands of years, radiation ruled; the famous cosmic microwave background radiation is thought to be a vestige of this era. Then matter started to dominate, and progressively larger astronomical structures condensed out. Now, if recent cosmological observations are correct, the expansion of the universe is beginning to accelerate— a sign that a strange new type of energy, perhaps springing from space itself, may be taking over.

Life as we know it depends on stars. But stars inevitably die, and their birth rate has declined dramatically since an initial burst about 10 billion years ago. About 100 trillion years from now, the last conventionally formed star will wink out, and a new era will commence. Processes currently too slow to be noticed will become important: the dispersal of planetary systems by stellar close encounters, the possible decay of ordinary and exotic matter, the slow evaporation of black holes.

Assuming that intelligent life can adapt to the changing circumstances, what fundamental limits does it face? In an eternal universe, potentially of infinite volume, one might hope that a sufficiently advanced civilization could collect an infinite amount of matter, energy and information. Surprisingly, this is not true. Even after an eternity of hard and well-planned labor, living beings could accumulate only a finite number of particles, a finite quantity of energy and a finite number of bits of information. What makes this failure all the more frustrating is that the number of available particles, ergs and bits may grow without bound. The problem is not necessarily the lack of resources but rather the difficulty in collecting them.

The culprit is the very thing that allows us to contemplate an eternal tenure: the expansion of the universe. As the cosmos grows in size, the average density of ordinary sources of energy declines. Doubling the radius of the universe decreases the density of atoms eightfold. For light waves, the decline is even more precipitous. Their energy density drops by a factor of 16 because the expansion stretches them and thereby saps their energy [see illustration below].

Figure 1. Dilution of the cosmos by the expansion of space affects different forms of energy in different ways. Ordinary matter (orange) thins out in direct proportion to volume, whereas the cosmic background radiation (purple) weakens even faster as it is stretched from light into microwaves and beyond. The energy density represented by a cosmological constant (blue) does not change, at least according to present theories.

As a result of this dilution, resources become ever more time-consuming to collect. Intelligent beings have two distinct strategies: let the material come to them or try to chase it down. For the former, the best approach in the long run is to let gravity do the work. Of all the forces of nature, only gravity and electromagnetism can draw things in from arbitrarily far away. But the latter gets screened out: oppositely charged particles balance one another, so that the typical object is neutral and hence immune to long-range electrical and magnetic forces. Gravity, on the other hand, cannot be screened out, because particles of matter and radiation only attract gravitationally; they do not repel.

Surrender to the Void

Even gravity, however, must contend with the expansion of the universe, which pulls objects apart and thereby weakens their mutual attraction. In all but one scenario, gravity eventually becomes unable to pull together larger quantities of material. Indeed, our universe may have already reached this point; clusters of galaxies may be the largest bodies that gravity will ever be able to bind together [see "The Evolution of Galaxy Clusters," by J. Patrick Henry, Ulrich G. Briel and Hans Bohringer; Scientific American, December 1998]. The lone exception occurs if the universe is poised between expansion and contraction, in which case gravity continues indefinitely to assemble ever greater amounts of matter. But that scenario is now thought to contradict observations, and in any event it poses its own difficulty: after 10^{33} years or so, the accessible matter will become so concentrated that most of it will collapse into black holes, sweeping up any life-forms. Being inside a black hole is not a happy condition. On the earth, all roads may lead to Rome, but inside a black hole, all roads lead in a finite amount of time to the center of the hole, where death and dismemberment are certain.

Sadly, the strategy of actively seeking resources fares no better than the passive approach does. The expansion of the universe drains away kinetic energy, so prospectors would have to squander their booty to maintain their speed. Even in the most optimistic scenario - in which the energy is traveling toward the scavenger at the speed of light and is collected without loss - a civilization could garner limitless energy only in or near a black hole. The latter possibility was explored by Steven Frautschi of the California Institute of Technology in 1982. He concluded that the energy available from the holes would dwindle more quickly than the costs of scavenging ***[see illustration below].*** We recently reexamined this possibility and found that the predicament is even worse than Frautschi thought. The size of a black hole required to sweep up energy forever exceeds the extent of the visible universe.

Figure 2. Energy collection strategy devised by physicist Steven Frautschi illustrates how difficult it will be to survive in the far future, 10^{100} or so years from now. In many cosmological scenarios, resources multiply as the universe - and any arbitrary reference sphere within it (blue sphere) expands and an increasing fraction of it becomes observable (red sphere). A civilization could use a black hole to convert matter— plundered from its empire (green sphere)— into energy. But as the empire grows, the cost of capturing new territory increases; the conquest can barely keep pace with the dilution of matter. In fact, matter will become so diluted that the civilization will not be able to safely build a black hole large enough to collect it.

> The cosmic dilution of energy is truly dire if the universe is expanding at an accelerating rate. All distant objects that are currently in view will eventually move away from us faster than the speed of light and, in doing so, disappear from view. The total resources at our disposal are therefore limited by what we can see today, at most ***[see below].***

The Worst of All Possible Universes

Among all the scenarios for an eternally expanding universe, the one dominated by the so-called cosmological constant is the bleakest. Not only is it unambiguous that life cannot survive eternally in such a universe, but the quality of life will quickly deteriorate as well. So if recent observations that the expansion is accelerating [see "Surveying Space-Time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; Scientific American, January 1999] are borne out, we could face a grim future.

Cosmic expansion carries objects away from one another unless they are bound together by gravity or another force. In our case, the Milky Way is part of a larger cluster of galaxies. About 10 million light-years across, this cluster remains a cohesive whole, whereas galaxies beyond it are whisked away as intergalactic space expands. The relative velocity of these distant galaxies is proportional to their distance. Beyond a certain distance called the horizon, the velocity exceeds the speed of light (which is allowed in the general theory of relativity because the velocity is imparted by the expansion of space itself). We can see no farther.

If the universe has a cosmological constant with a positive value, as the observations suggest, the expansion is accelerating: galaxies are beginning to move apart ever more rapidly. Their velocity is still proportional to their distance, but the constant of proportionality remains constant rather than decreasing with time, as it does if the universe decelerates. Consequently, galaxies that are now beyond our horizon will forever remain out of sight. Even the galaxies we can currently see - except for those in the local cluster - will eventually attain the speed of light and vanish from view. The acceleration, which resembles inflation in the very early universe, began when the cosmos was about half its present age.

The disappearance of distant galaxies will be gradual. Their light will stretch out until it becomes undetectable. Over time, the amount of matter we can see will decrease, and the number of worlds our starships can reach will diminish. Within two trillion years, well before the last stars in the universe die, all objects outside our own cluster of galaxies will no longer be observable or accessible. There will be no new worlds to conquer, literally. We will truly be alone in the universe.

Expanding universe looks dramatically different depending on whether the growth is decelerating ***(upper sequence)*** or accelerating ***(lower sequence).*** In both cases, the universe is infinite, but any patch of space— demarcated by a reference sphere that represents the distance to particular galaxies - enlarges (***blue sphere).*** We can see only a limited volume, which grows steadily as light signals have time to propagate ***(red sphere).*** If expansion is decelerating, we can see an increasing fraction of the cosmos. More and more galaxies fill the sky. But if expansion is accelerating, we can see a decreasing fraction of the cosmos. Space seems to empty out.

Not all forms of energy are equally subject to the dilution. The universe might, for example, be filled with a network of cosmic strings— infinitely long, thin concentrations of energy that could have developed as the early universe cooled unevenly. The energy per unit length of a cosmic string remains unchanged despite cosmic expansion [see "Cosmic Strings," by Alexander Vilenkin; Scientific American, December 1987]. Intelligent beings might try to cut one, congregate around the loose ends and begin consuming it. If the string network is infinite, they might hope to satisfy their appetite forever. The problem with this strategy is that whatever lifeforms can do, natural processes can also do. If a civilization can figure out a way to cut cosmic strings, then the string network will fall apart of its own accord. For example, black holes may spontaneously appear on the strings and devour them. Therefore, the beings could swallow only a finite amount of string before running into another loose end. The entire string network would eventually disappear, leaving the civilization destitute.

What about mining the quantum vacuum? After all, the cosmic acceleration may be driven by the so-called cosmological constant, a form of energy that does not dilute as the universe expands [see

"Cosmological Antigravity," by Lawrence M. Krauss; Scientific American, January]. If so, empty space is filled with a bizarre type of radiation, called Gibbons-Hawking or de Sitter radiation Alas, it is impossible to extract energy from this radiation for useful work. If the vacuum yielded up energy, it would drop into a lower energy state, yet the vacuum is already the lowest energy state there is.

No matter how clever we try to be and how cooperative the universe is, we will someday have to confront the finiteness of the resources at our disposal. Even so, are there ways to cope forever?

The obvious strategy is to learn to make do with less, a scheme first discussed quantitatively by Dyson. In order to reduce energy consumption and keep it low despite exertion, we would eventually have to reduce our body temperature. One might speculate about genetically engineered humans who function at somewhat lower temperatures than 310 kelvins (98.6 degrees Fahrenheit). Yet the human body temperature cannot be reduced arbitrarily; the freezing point of blood is a firm lower limit. Ultimately, we will need to abandon our bodies entirely.

While futuristic, the idea of shedding our bodies presents no fundamental difficulties. It presumes only that consciousness is not tied to a particular set of organic molecules but rather can be embodied in a multitude of different forms, from cyborgs to sentient interstellar clouds [see "Will Robots Inherit the Earth?" by Marvin Minsky; Scientific American, October 1994]. Most modern philosophers and cognitive scientists regard conscious thought as a process that a computer could perform. The details need not concern us here (which is convenient, as we are not competent to discuss them). We still have many billions of years to design new physical incarnations to which we will someday transfer our conscious selves. These new "bodies" will need to operate at cooler temperatures and at lower metabolic rates - that is, lower rates of energy consumption.

Dyson showed that if organisms could slow their metabolism as the universe cooled, they could arrange to consume a finite total amount of energy over all of eternity. Although the lower temperatures would also slow consciousness - the number of thoughts per second - the rate would remain large enough for the total number of thoughts, in principle, to be unlimited. In short, intelligent beings could survive forever, not just in absolute time but also in subjective time. As long as organisms were guaranteed to have an infinite number of thoughts, they would not mind a languid pace of life. When billions of years stretch out before you, what's the rush?

At first glance, this might look like a case of something for nothing. But the mathematics of infinity can defy intuition. For an organism to maintain the same degree of complexity, Dyson argued, its rate of information processing must be directly proportional to body temperature, whereas the rate of energy consumption is proportional to the square of the temperature (the additional factor of temperature comes from basic thermodynamics). Therefore, the power requirements slacken faster than cognitive alacrity does ***[see illustration below].*** At 310 kelvins, the human body expends approximately 100 watts. At 155 kelvins, an equivalently complex organism could think at half the speed but consume a quarter of the power. The trade-off is acceptable because physical processes in the environment slow down at a similar rate.

Eternal life on finite energy? If a new form of life could lower its body temperature below the human value of 310 kelvins (98.6 degrees Fahrenheit), it would consume less power, albeit at the cost of thinking more sluggishly (***top graph).*** Because metabolism would decline faster than cognition, the life-form could arrange to have an infinite number of thoughts on limited resources. One caveat is that its ability to dissipate waste heat would also decline, preventing it from cooling below about 10-13 kelvin. Hibernation ***(bottom graph)*** might eliminate the problem of heat disposal. As the life-form cools, it would spend an increasing fraction of its time dormant, further reducing its average metabolic rate and cognitive speed. In this way, the power consumption could always remain lower than the maximum rate of heat dissipation, while still allowing for an infinite number of thoughts. But such a scheme might run afoul of other problems, such as quantum limits.

To Sleep, to Die

Unfortunately, there is a catch. Most of the power is dissipated as heat, which must escape usually by radiating away - if the object is not to heat up. Human skin, for example, glows in infrared light. At very low temperatures, the most efficient radiator would be a dilute gas of electrons. Yet the efficiency even of this optimal radiator declines as the cube of the temperature, faster than the decrease in the metabolic rate. A point would come when organisms could not lower their temperature further. They would be forced instead to reduce their complexity— to dumb down. Before long, they could no longer be regarded as intelligent.

To the timid, this might seem like the end. But to compensate for the inefficiency of radiators, Dyson boldly devised a strategy of hibernation. Organisms would spend only a small fraction of their time awake. While sleeping, their metabolic rates would drop, but - crucially - they would continue to dissipate heat. In this way, they could achieve an ever lower average body temperature ***[see illustration on opposite page].*** In fact, by spending an increasing fraction of their time asleep, they could consume a finite amount of energy yet exist forever and have an infinite number of thoughts. Dyson concluded that eternal life is indeed possible.

Since his original paper, several difficulties with his plan have emerged. For one, Dyson assumed that the average temperature of deep space - currently 2.7 kelvins, as set by the cosmic microwave background radiation - would always decrease as the cosmos expands, so that organisms could continue to decrease their temperature forever. But if the universe has a cosmological constant, the temperature has an absolute floor fixed by the Gibbons-Hawking radiation. For current estimates of the value of the cosmological constant, this radiation has an effective temperature of about 10^{-29} kelvin. As was pointed out independently by cosmologists J. Richard Gott II, John Barrow, Frank Tipler and us, once organisms had cooled to this level, they could not continue to lower their temperature in order to conserve energy.

The second difficulty is the need for alarm clocks to wake the organisms periodically. These clocks would have to operate reliably for longer and longer times on less and less energy. Quantum mechanics suggests that this is impossible. Consider, for example, an alarm clock that consists of two small balls that are taken far apart and then aimed at each other and released. When they collide, they ring a bell. To lengthen the time between alarms, organisms would release the balls at a slower speed. But eventually the clock will run up against constraints from Heisenberg's uncertainty principle, which prevents the speed and position of the balls from both being specified to arbitrary precision. If one or the other is sufficiently inaccurate, the alarm clock will fail, and hibernation will turn into eternal rest.

One might imagine other alarm clocks that could forever remain above the quantum limit and might even be integrated into the organism itself. Nevertheless, no one has yet come up with a specific mechanism that could reliably wake an organism while consuming finite energy.

The Eternal Recurrence of the Same

The third and most general doubt about the long-term viability of intelligent life involves fundamental limitations on computation. Computer scientists once thought it was impossible to compute without expending a certain minimum amount of energy per operation, an amount that is directly proportional to the temperature of the computer. Then, in the early 1980s, researchers realized that certain physical processes, such as quantum effects or the random Brownian motion of a particle in a fluid, could serve as the basis for a lossless computer [see "The Fundamental Physical Limits of Computation," by Charles H. Bennett and Rolf Landauer; Scientific American, July 1985]. Such computers could operate with an arbitrarily small amount of energy. To use less, they simply slow down— a trade-off that eternal organisms may be able to make. There are only two conditions. First, they must remain in thermal equilibrium with their environment. Second, they must never discard information. If they did, the computation would become irreversible, and thermodynamically an irreversible process must dissipate energy.

Unhappily, those conditions become insurmountable in an expanding universe. As cosmic expansion dilutes and stretches the wavelength of light, organisms become unable to emit or absorb the radiation they would need to establish thermal equilibrium with their surroundings. And with a finite amount of material at their disposal, and hence a finite memory, they would eventually have to forget an old thought in order to have a new one. What kind of perpetual existence could such organisms have, even in principle? They could collect only a finite number of particles and a finite amount of information. Those particles and bits could be configured in only a finite number of ways. Because thoughts are the reorganization of information, finite information implies a finite number of thoughts. All organisms would ever do is relive the past, having the same thoughts over and over again. Eternity would become a prison, rather than an endlessly receding horizon of creativity and exploration. It might be nirvana, but would it be living?

It is only fair to point out that Dyson has not given up. In his correspondence with us, he has suggested that life can avoid the quantum constraints on energy and information by, for example, growing in size or using different types of memory. As he puts it, the question is whether life is "analog" or "digital" - that is, whether continuum physics or quantum physics sets its limits. We believe that over the long haul life is digital.

Is there any other hope for eternal life? Quantum mechanics, which we argue puts such unbending limits on life, might come to its rescue in another guise. For example, if the quantum mechanics of gravity allows the existence of stable wormholes, life-forms might circumvent the barriers erected by the speed of light, visit parts of the universe that are otherwise inaccessible, and collect infinite amounts of energy and information. Or perhaps they could construct "baby" universes [see "The Self-Reproducing Inflationary Universe," by Andrei Linde; Scientific American, November 1994] and send themselves, or at least a set of instructions to reconstitute themselves, through to the baby universe. In that way, life could carry on.

The ultimate limits on life will in any case become significant only on timescales that are truly cosmic. Still, for some it may seem disturbing that life, certainly in its physical incarnation, must come to an end. But to us, it is remarkable that even with our limited knowledge, we can draw conclusions about such grand issues. Perhaps being cognizant of our fascinating universe and our destiny within it is a greater gift than being able to inhabit it forever.

The Authors

Lawrence M. Krauss and Glenn D**.** Starkman consider their ruminations on the future of life as a natural extension of their interest in the fundamental workings of the universe. Krauss's books on the predictions of science fiction, ***The Physics of Star Trek*** and ***Beyond Star Trek,*** have a similar motivation. The chair of the physics department at Case Western Reserve University in Cleveland, Krauss was among the first cosmologists to argue forcefully that the universe is dominated by a cosmological constant— a view now widely shared. Starkman, also a professor at Case Western, is perhaps best known for his work on the topology of the universe. Both authors are frustrated optimists. They have sought ways that life could persist forever, to no avail. Nevertheless they maintain the hope that the Cleveland Indians will win the World Series in the ample time that remains.

Further Reading

TIME WITHOUT END: PHYSICS AND BIOLOGY IN AN OPEN UNIVERSE. Freeman J. Dyson in ***Reviews of Modern Physics,*** Vol. 51, No. 3, pages 447-460;July 1979.

THE ANTHROPIC COSMOLOGICAL PRINCIPLE. John D. Barrow and Frank J. Tipler. Oxford University Press, 1988.

THE LAST THREE MINUTES: CONJECTURES ABOUT THE ULTIMATE FATE OF THE UNIVERSE. Paul C. W. Davies. Harper Collins, 1997.

THE FIVE AGES OF THE UNIVERSE: INSIDE THE PHYSICS OF ETERNITY. Fred Adams and Greg Laughlin. Free Press, 1999.

QUINTESSENCE: THE MYSTERY OF THE MISSING MASS. Lawrence M. Krauss. Basic Books, 1999.

LIFE, THE UNIVERSE, AND NOTHING: LIFE AND DEATH IN AN EVER EXPANDING UNIVERSE. Lawrence M. Krauss and Glenn D. Starkman in ***Astrophysical Journal***(in press). Available at xxx.lanl.gov/abs/astro-ph/9902189 on the World Wide Web.

Milestones on the road to eternity range from the big bang through the birth and death of stars (***see timelines below***). As the last stars wane, intelligent beings will need to find new sources of energy, such as cosmic strings (***illustration above***). Unfortunately, natural processes - such as outbreaks of black holes - will erode these linear concentrations of energy, eventually forcing life-forms to seek sustenance elsewhere, if they can find it. Because the governing processes of the universe act on widely varying timescales, the timeline is best given a logarithmic scale. If the universe is now expanding at an accelerating rate, additional effects (shown on the timeline in blue) will make life even more miserable.

Time Scale from the Beginning to the End of the Universe